Transient DDES computations of the NREL Phase-VI rotor in axial flow conditions

Sørensen, Niels N.; Schreck, Scott

Publication date:
2012

Transient DDES computations of the NREL Phase-VI rotor in axial flow conditions

Niels N. Sørensen[1] and Scott Schreck[2]

[1] Wind Energy Department · DTU, Risø Campus, DK
[2] NREL's National Wind Technology Center, Golden, CO 80401, US.

Background

The NREL Phase-VI measurements:

- The NREL/NASA Ames Phase-VI measurements include time resolved signals
- For CFD validation main focus have been on mean loads
- The data are well suited for investigating unsteady aerodynamics

We want to test the Transitional DDES approach against measurements and RANS predictions:

- With respect to mean quantities (LSSTQ, pressure)
- Unsteady loading (C_{thrust})
- Improved physical understanding (Shedding frequency)

Flow Modeling
Methodology

Measurements:

- S-series from the **Unsteady Aerodynamics Experiment Phase VI**
- Upwind configuration zero cone and zero yaw angle

Rotor Diameter [m]	RPM	Blade Pitch [deg]	Wind Speed [m/s]
10.058	71.9	3	(10,12,13,15,20)

Flow Solver:

- DDES turbulence modelling
- Correlation based laminar/turbulent transition modelling

Flow Modeling

In-house flow solver, EllipSys3D.

- Incompressible Navier-Stokes equations
- Rotation enforced through a moving grid option (ready to do dynamic stall)
- Turbulence is modelled by DDES model
- Transition modeling, $\gamma - Re_\theta$ correlation based model
- Second order accurate in times
- Convective terms is modelled by QUICK + CDS4
- Time-step [1000-2000] per revolution, with 12-6 sub-iterations
- The computations are accelerated by using a three level grid sequence
- 6-8 hours per revolution using 136 CPU's

Transitional $k - \omega$ model DDES

- Eddy viscosity

$$\mu_t = \frac{\rho a_1 k}{\max(a_1\omega; F_2\Omega)}$$

- Transport equation for turbulent kinetic

$$\rho\frac{\partial k}{\partial t} + \rho U_j\frac{\partial k}{\partial x_j} = \tau_{ij}\frac{\partial U_i}{\partial x_j}\gamma_{eff} - \rho\beta^* k\omega F_{DDES}\Gamma + \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right]$$

- Transport equation for the specific dissipation rate

$$\rho\frac{\partial \omega}{\partial t} + \rho U_j\frac{\partial \omega}{\partial x_j} = \frac{\gamma}{\nu_t}\tau_{ij}\frac{\partial U_i}{\partial x_j} - \beta\rho\omega^2 + 2\rho(1-F_1)\frac{1}{\sigma_{\omega 2}\omega}\frac{\partial k}{\partial x_j}\frac{\partial \omega}{\partial x_j} + \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_\omega}\right)\frac{\partial \omega}{\partial x_j}\right]$$

DES and DDES modeling

The idea behind the DES modeling is to exchange the turbulent length scale with the grid size when the turbulent length scale become larger than the grid size, and the grid is capable of resolving some of the scales.

- The turbulent length scale in the $k - \omega$ model is given by

$$L_t^{k-\omega} = \frac{k^{\frac{3}{2}}}{\epsilon} = \frac{\sqrt{k}}{\beta^* \omega} \text{ using } \epsilon = \beta^* k\omega$$

- The turbulent length scale in a LES would be

$$L_t^{LES} = \Delta C_{Des} \text{ with } \Delta = \max\left[\Delta x, \Delta y, \Delta z\right]$$

- To enforce the L_t^{LES} when the grid allows, we will simply scale the dissipation term in the k equation by the ratio between $L_t^{k-\omega}$ and L_t^{LES}.

$$F_{DDES} = \max\left(\frac{L_t^{k-\omega}}{L_t^{DES}}(1 - F_{Shield}); 1\right)$$

The $\gamma - Re_\theta$ Correlation based laminar/turbulent transition model

The model uses two transport equations, one for the intermittency γ and one for the transition onset momentum thickness Reynolds number $Re_{\theta t}$

$$\frac{\partial(\rho\gamma)}{\partial t} + \frac{\partial(\rho U_j \gamma)}{\partial x_j} = P_\gamma - E_\gamma + \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_f}\right)\frac{\partial\gamma}{\partial x_j}\right] .$$

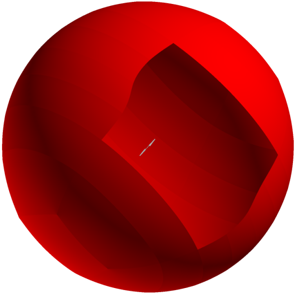
$$\frac{\partial(\rho\widetilde{\mathrm{Re}}_{\theta t})}{\partial t} + \frac{\partial(\rho U_j \widetilde{\mathrm{Re}}_{\theta t})}{\partial x_j} = P_{\theta t} + \frac{\partial}{\partial x_j}\left[\sigma_{\theta t}(\mu + \mu_t)\frac{\partial\widetilde{\mathrm{Re}}_{\theta t}}{\partial x_j}\right] .$$

Leaving out some details the model delivers an effective intermittency γ_{eff} in every point of the domain, including natural transition, by-pass transition and separation induced transition.

$$\Gamma = \min\left(\max(\gamma_{eff}, 0.1), 1.0\right)$$

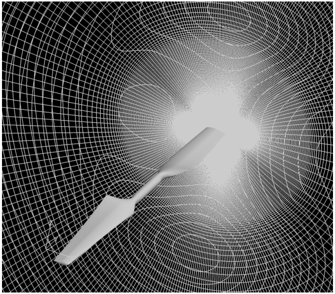
Computational Grid

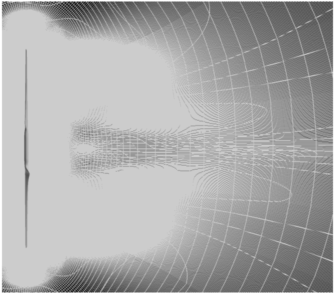
- The domain is 20 rotor diameters in diameter
- Chord-wise 256, Span-wise 256



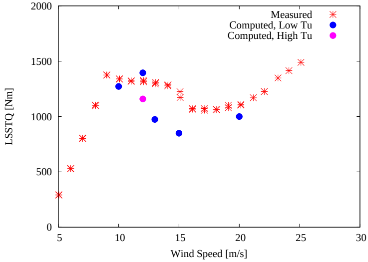
Domain and grid
Computational Grid

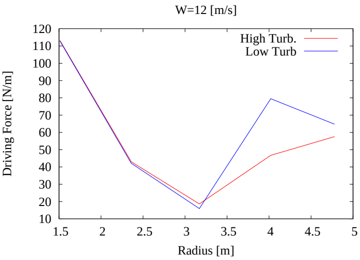
- O-O-Topology of 136 blocks of $64^3 \sim 36$ Million points
- The wall normal y^+ is less than two on the blade surface





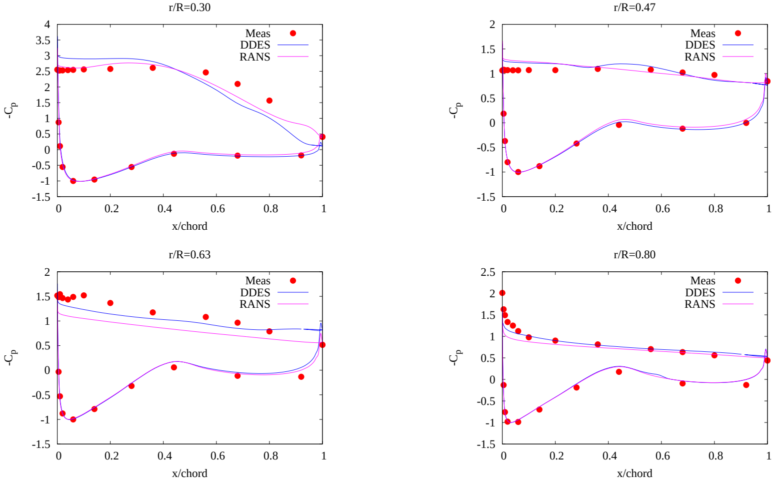
Results, The influence of transition
Low Speed Shaft Torque





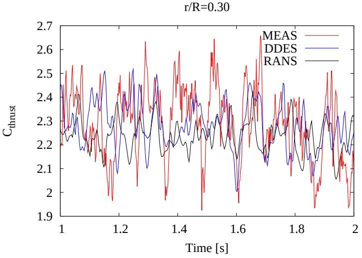
- For the power curve the effect of by-pass transition mainly plays a role around onset of stall
- Locally on the blade the impact of transition is mainly seen at the tip where we have the lowest AOA's

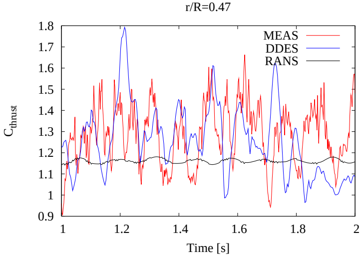
Results, Comparison between RANS and DDES
Pressure distributions, w=15 m/s



N. N. Sørensen, DTU and S. Schreck, NREL

Results, Comparison between RANS and DDES
Time traces of the loads

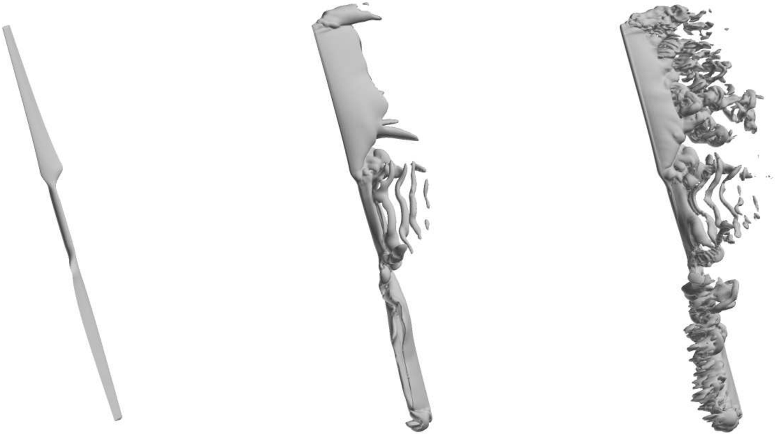




Results, Comparison between RANS and DDES

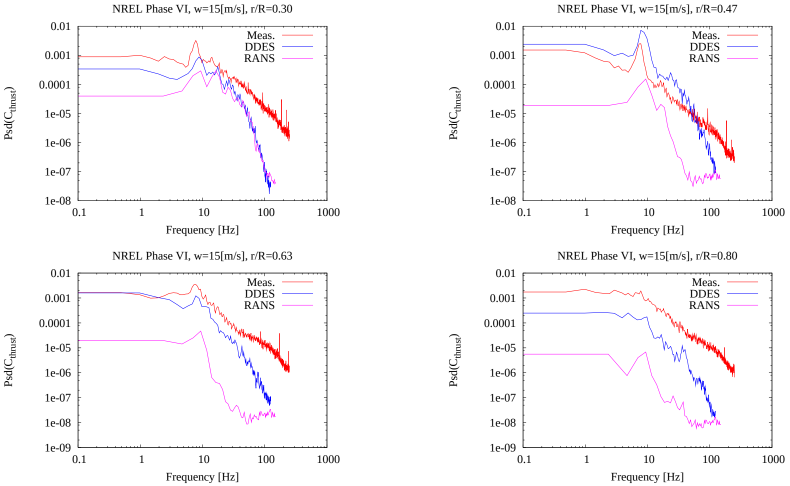
Wake at 15 m/s

Geometry | RANS | DDES

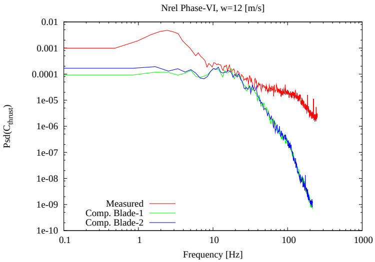


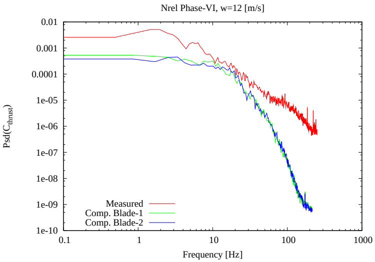
Results, Comparison between RANS and DDES

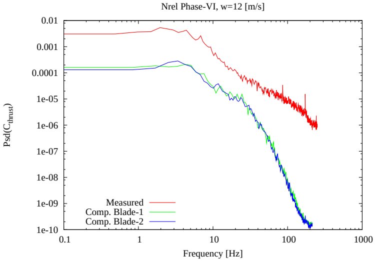
Power Spectral Density based on C_{thrust}

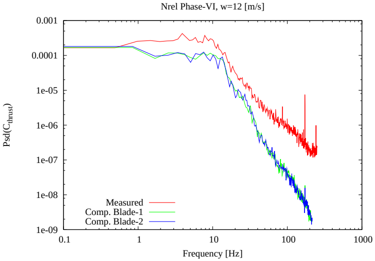


PSD of the Thrust Coefficient, 12 m/s





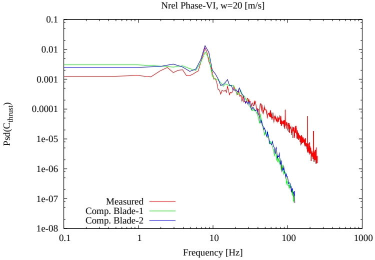


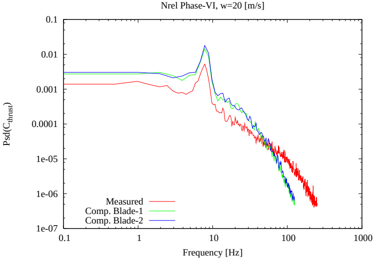


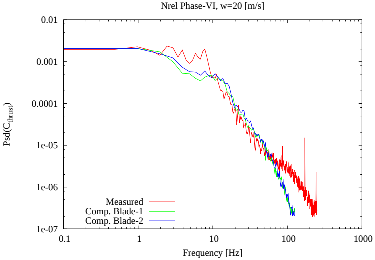
N. N. Sørensen, DTU and S. Schreck, NREL

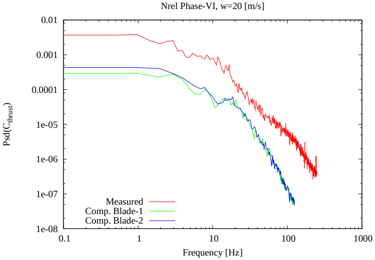
Results, PSD of C_{thrust}

PSD of the Thrust Coefficient, 20 m/s

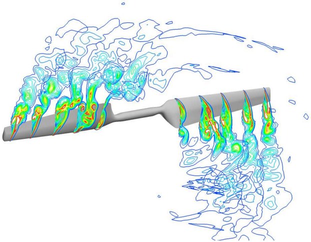


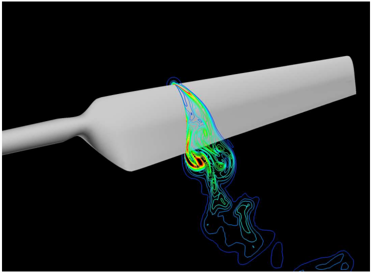






Results, physics of the shedding
Shedding at 15 m/s





Strouhal Numbers and Frequencies, w=15 m/s

The Strouhal number can be defined by:

$$St = \frac{f\, c\, \sin\alpha}{U_{eff}}$$

and α is the geometrical AOA for simplicity.

Radius	U_{eff}	α [deg]	f [1/s]	St
0.30	18.8	38.5	7.8	0.18
0.47	23.3	35.5	7.4	0.12
0.63	28.2	31.0	7.6	0.08
0.80	33.8	26.7	7.8	0.05

Conclusions

We have shown that

- DDES do not improve the power prediction compared to RANS predictions
- DDES can predict the energy contents of the unsteady flow much better than RANS
- DDES fails to capture the high frequency fluctuations
- DDES can capture the low frequency shedding along the blade in cases with flow separation
- The shedding frequency for the NREL Phase-VI blade seem to be controlled by the root flow
- The by-pass transition process can heavily influence the stalling behaviour